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13. ABSTRACT (Maximum 200 words) The goal of the MURI project is to advance matter wave sensors by combining atom interferometry with atom lasers and atom waveguides. This has the prospect of improving the sensitivity of such sensors by orders of magnitude as compared with existing state-of-the-art sensors. This final report summarize major steps towards this goal, including the study of wave guides using atom chips, the demonstration of the novel method of contrast interferometry with Bose-Einstein condensates, and the realization of a prototype trapped atom interferometer using optical potentials. Furthermore, other scientific contributions of Jamil Abo-Shaeer, the student supported by the MURI fellowship, are reported: the study of vortices, sound and ultracold molecules.				
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Enclosure 1

FINAL PROGRESS REPORT

Strategic Applications of Ultra-Cold Atoms MURI Fellowship for J.R. Abo-Shaeer

Statement of the problem studied

The MURI consortium is a focused collaborative program to advance matter wave sensors. The goal is to combine atom interferometry with atom lasers and atom waveguides with the prospect of improving the sensitivity of such sensors by orders of magnitude as compared with existing state-of-the-art sensors.

Summary of the most important results

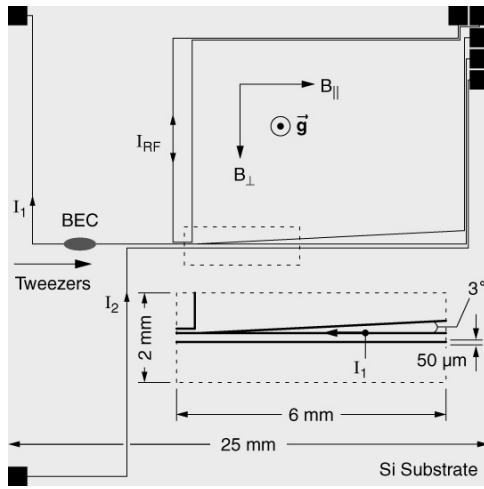
All papers on sodium BEC at MIT acknowledge ARO support since there is some overlap and collaboration between the activities of the three sodium labs in our group. In the first part of this report, we summarize the most important results which are directly connected to the goals of the MURI collaboration. In the second part, we summarize the results in which Jamil Abo-Shaeer, the student supported by the MURI fellowship, played a major role.

Major results on matter wave interferometry

1. Propagation of Bose-Einstein condensates in a magnetic waveguide

Progress in the field of atom optics depends on developing improved sources of matter waves and advances in their coherent manipulation. Miniaturizing the current carrying structures used to confine Bose-Einstein condensates offer prospects for finer control over the clouds. We have demonstrated that a gaseous Bose-Einstein condensate transported with optical tweezers [1] can be transferred into a magnetic trap microfabricated on a silicon substrate (see figure) [2]. This has opened up a front on which further techniques for coherent condensate transport and manipulation can be explored.

We released the condensate from the magnetic microtrap into a single-wire magnetic waveguide and studied its propagation. Condensates were observed to propagate 12 mm before exiting the field-of-view of our imaging system. We observed single-mode (excitation-less) condensate propagation along homogeneous segments of the waveguide. Transverse excitations were created in condensates propagating through perturbations in the guiding potential. These perturbations resulted from geometric deformations of the current carrying wires on the substrate. Finer imperfections were observed when trapped condensates were brought closer to the microchip as evidenced by the longitudinal fragmentation of the cloud. Such imperfections have to be controlled in order to use atom chips for precision atom interferometry.

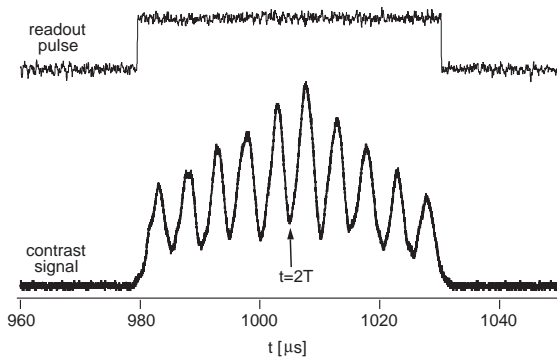


Microfabricated magnetic trap and waveguide. Optical tweezers loaded a Bose-Einstein condensate into the microtrap formed by currents I_1 and I_2 in conjunction with the magnetic bias field B_{\perp} . Lowering I_2 to zero released the condensate into a single-wire magnetic waveguide. Atom flow was from left to right. The condensate was trapped above the plane of the page and the gravitational acceleration, \vec{g} , points out of the page. All microfabricated features are drawn to scale.

2. Contrast interferometry using Bose-Einstein condensates to measure h/m and α

We have demonstrated a new atom interferometer scheme, which shows promise for a high precision measurement of the recoil energy of an atom [3]. A precise measurement of the recoil frequency will lead to a more precise determination of h/m and of the fine structure constant α .

Our interferometer extends previous schemes used at Stanford [4] and New York [5], and combines their advantages. Optical standing wave pulses were used to create a symmetric three-path interferometer. This configuration encodes the photon recoil phase in the contrast of the interference fringes, rather than in their phase. Because it is insensitive to the fringe phase, the method is not sensitive to vibrations, accelerations, or rotations. The symmetry also suppresses errors from magnetic field gradients, and our use of only one internal state suppresses errors arising from differences in the ac Stark shifts between different internal states. A crucial aspect of this new interferometer is the use of atomic samples with sub-recoil momentum distribution. We use a Bose-Einstein condensate (BEC) as a bright sub-recoil atom source. This allows the contrast oscillations to persist for many cycles, permitting precise determination of the recoil phase in a single “shot.”



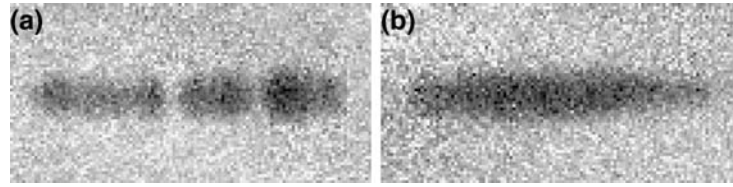
Typical single-shot signal from the contrast interferometer. The contrast signal is the intensity of a laser beam reflected by the interfering atomic matter waves. It represents the beat note between two simple interference patterns. Ten oscillations with 60 % are observed during the 50 μ s readout.

3. Bose-Einstein condensates near a microfabricated surface

Microfabricated chips with current-carrying wires can confine ultracold atoms more tightly and in more complex geometries. However, previous experiments revealed unexpected phenomena when ultracold atoms were trapped very close to microfabricated surfaces: Fragmentation of the cloud, and shortening of the lifetime were observed. In this study, we compared magnetically and optically confined Bose-Einstein condensates near a microfabricated surface [6]. Since the two traps operate on different principles, this study provided a unique examination of the interaction between Bose-Einstein condensates and a microfabricated surface.

Condensate fragmentation observed in microfabricated magnetic traps was not observed in optical dipole traps at the same location. Therefore, the corrugated potential was created by the current carrying wires. The

measured condensate lifetime was >20 s and independent of the atom-surface separation under both magnetic and optical confinement. The much shorter lifetimes observed elsewhere were probably due to technical noise. Radio-frequency spin-flip transitions driven by technical noise were directly observed for optically confined condensates and could limit the condensate lifetime in microfabricated magnetic traps.

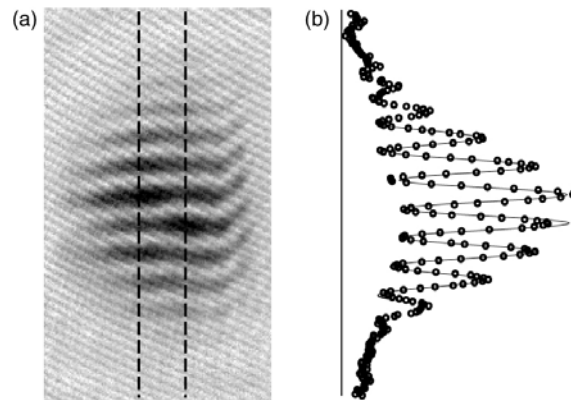


Fragmentation of Bose-Einstein condensates. Radial absorption images after 10 ms ballistic expansion of condensates containing $\approx 10^6$ atoms after holding at a distance of $85\text{ }\mu\text{m}$ from the microfabricated surface for 15 s in the (a) microfabricated magnetic trap and (b) optical dipole trap. Longitudinal fragmentation occurred for condensates held in the microfabricated magnetic trap, but not for those confined optically at the same location with the microfabricated magnetic trap off. The field of view is $0.5\text{ mm} \times 1.0\text{ mm}$.

4. Atom interferometry with Bose-Einstein condensates in a double-well potential

The applicability, accuracy, and sensitivity of atom interferometers may be improved by exploiting the laser-like coherence properties of gaseous Bose-Einstein condensates in combination with the fine manipulation capabilities of atomic microtraps and waveguides. Current proposals for microtrap and waveguide interferometers utilize double-well potentials for beam splitters and recombiners. To implement a prototype of such schemes, we created a trapped-atom interferometer using gaseous Bose-Einstein condensates coherently split by deforming an optical single-well potential into a double-well potential [7].

Sodium condensates were split by deforming an initially single-well potential into two wells separated by $13\text{ }\mu\text{m}$. To avoid deleterious mean field effects common to traditional in-trap recombination schemes, the relative phase between the two condensates was determined from the spatial phase of the matter wave interference pattern formed upon releasing the atoms from the separated potential wells. The coherence time of the separated condensates was measured to be 5 ms, and was set by technical limitations of our current setup. The large separation between the split potential wells allowed the phase of each condensate to evolve independently and either condensate to be addressed individually.



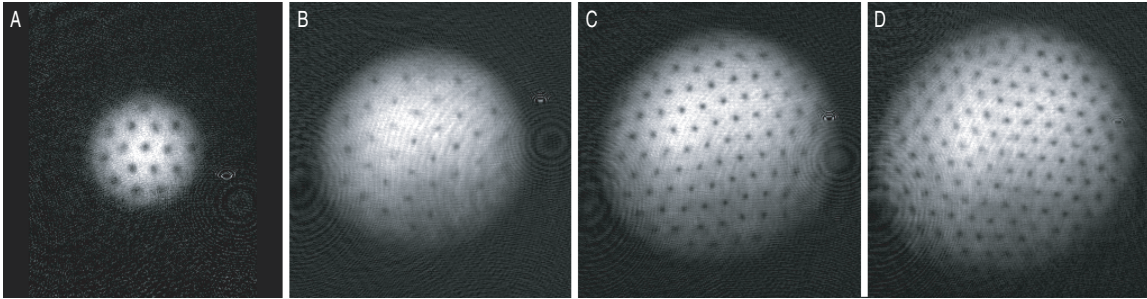
Matter wave interference. (a) Absorption image of condensates released from the optical double-well potential and allowed to expand for 30 ms. The field of view is $600\text{ }\mu\text{m} \times 350\text{ }\mu\text{m}$. (b) Radial density profiles were obtained by integrating the absorption signal between the dashed lines, and typical interference patterns had $> 60\%$ contrast. The spatial phase of the matter wave interference pattern was extracted from the fit shown.

Major results obtained by Jamil Abo-Shaeer, the graduate student supported by the MURI fellowship

1. Observation of Vortex Lattices in Bose-Einstein Condensates

Quantized vortices play a key role in superfluidity and superconductivity. In superconductors, magnetic flux lines arrange themselves in regular lattices that have been directly imaged. In superfluids, direct observation of vortices had been limited to small arrays (up to 11 vortices), both in liquid ^4He [8] and more recently in rotating gaseous Bose-Einstein condensates (BEC) [9, 10].

We have observed the formation of highly-ordered vortex lattices in a rotating Bose-condensed gas [11]. They were produced by rotating the condensate around its long axis using the optical dipole force exerted by a blue-detuned laser. A striking feature of the observed lattices is the extreme regularity, free of any major distortions, even near the boundary. Such “Abrikosov” lattices were first predicted for quantized magnetic flux lines in type-II superconductors. The observed triangular lattices contained over 100 vortices with lifetimes of several seconds. Individual vortices persisted up to 40 s. The lattices could be generated over a wide range of rotation frequencies and trap geometries, shedding light on the formation process. Our observation of lattice dislocations, irregular structure and dynamics indicate that gaseous Bose-Einstein condensates may be a model system for the study of vortex matter.

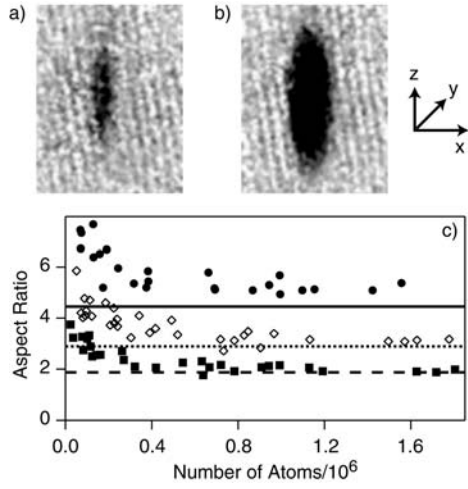


Observation of vortex lattices. The examples shown contain (A) 16 (B) 32 (C) 80 and (D) 130 vortices. The vortices have “crystallized” in a triangular pattern. The diameter of the cloud in (D) was 1 mm after ballistic expansion which represents a magnification of 20.

2. Realization of Bose-Einstein condensates in lower dimensions

Bose-Einstein condensates of sodium atoms have been prepared in optical and magnetic traps in which the energy-level spacing in one or two dimensions exceeds the interaction energy between atoms. This realized condensates of lower dimensionality [12]. In anisotropic traps, a primary indicator of crossing the transition temperature for Bose-Einstein condensation is a sudden change of the aspect ratio of the ballistically expanding cloud. The transition to lower dimensions is a smooth cross-over, but has similar indicators. In the 3D Thomas-Fermi limit the degree of anisotropy of a BEC is independent of the number N of atoms, whereas in 1D and 2D, the aspect ratio depends on N . This was used in our experiments as a distinctive feature of lower dimensionality.

In our traps, the ratio of the highest to lowest frequency was about 100. Due to this extreme geometry the number of atoms at the cross-over to lower-dimensionality was rather large ($> 10^5$ in the 2D case) which provides a good starting point for the exploration of phenomena which only occur in one or two dimensions.



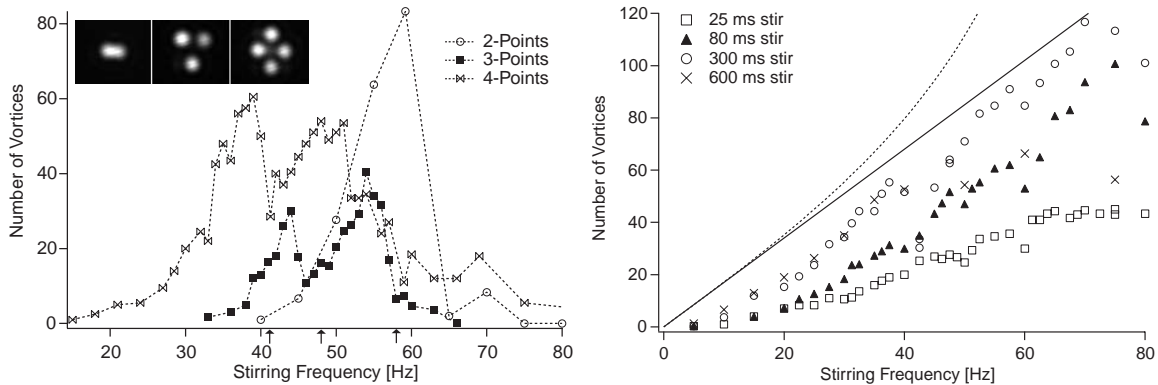
Cross-over from 3D to 2D condensates observed in the change of the aspect ratio. Condensates were released from a disk-shaped optical trap and observed after 15 ms time-of-flight. a) (2D) condensate with 9×10^4 atoms b) (3D) condensate with 8×10^5 atoms in a trap with vertical trap frequency of 790 Hz. c) Aspect ratio as a function of atom number for optical traps with vertical trap frequencies of 1620 Hz (filled circles), 790 Hz (open diamonds) and 450 Hz (filled squares). The lines indicate the aspect ratios as expected for condensates in the 3D (Thomas-Fermi) regime. We attribute discrepancies between expected and measured aspect ratio for large numbers to the influence of anharmonicities on the measurement of the trap frequencies.

3. Vortex Nucleation in a Stirred Bose-Einstein Condensate

Dissipation and turbulence in superfluid flow often involves the creation and subsequent motion of quantized vortices. Since vortices are topological defects they may only be created in pairs, or can enter a system individually from its boundary. The nucleation process has been a subject of much theoretical interest [13]. Experiments with Bose-Einstein condensates in atom traps are well suited to test theories of nucleation because the boundary of the condensate is well controlled, and vortices can be directly imaged.

In previous work, we had observed vortex lattices in stirred Bose-Einstein condensates [11]. By varying the stirring parameters we explored different mechanisms for vortex nucleation [14]. A large stirrer, with a beam waist comparable to the condensate radius showed enhanced vortex generation at discrete frequencies. The figure shows the number of vortices versus the frequency of rotation of the laser beam using 2-, 3- and 4-point patterns for the stirring beams. These resonances were close to the frequencies of excitation for surface modes of different multipolarity. This observation confirms the role of discrete surface modes in vortex formation.

However, when we used a tightly focused (beam waist 5 μm) laser beam as stirrer, we observed a broad response as a function of the frequency of the stirrer's motion, and no resonances (see figure). Furthermore, vortices could be generated well below the critical rotation frequency for the excitation of surface modes. This suggests a local mechanism of vortex generation involving hydrodynamic flow and local turbulence.



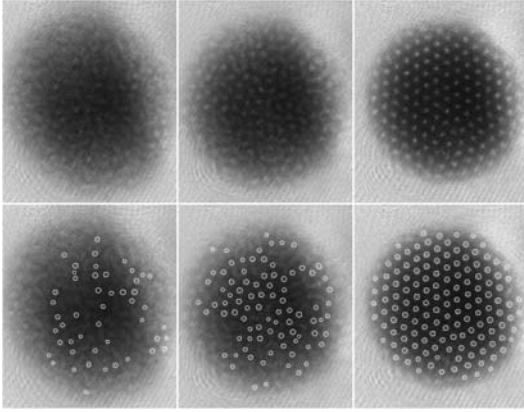
Discrete resonances in vortex nucleation (left). The number of vortices created by multi-point patterns is shown. The arrows below the graph show the positions of the surface mode resonances. The stirring times were 100 ms for the 2- and 3-point data, and 300 ms for the 4-point data. Inset shows 2-, 3-, and 4-point dipole potentials produced by a 25 μm waist laser beam imaged onto the CCD camera.

Non-resonant nucleation using a small stirrer (right). Average number of vortices created for different stirring times using a 2-point pattern positioned at the edge of the condensate.

4. Formation and Decay of Vortex Lattices in Bose-Einstein Condensates at Finite Temperatures

Gaseous Bose-Einstein condensates (BEC) are a testbed for many-body theory. Recently, rotating condensates and vortices have become the focus of many theoretical and experimental studies [13]. We have done the first quantitative investigation of vortex dynamics at finite temperature [15].

The decay of the vortex lattice was observed non-destructively by monitoring the centrifugal distortions of the rotating condensate. The formation of the vortex lattice could be deduced from the increasing contrast of the vortex cores observed in ballistic expansion. In contrast to the decay, the formation of the vortex lattice was insensitive to temperature. Both processes are dissipative and require physics beyond the Gross-Pitaevskii equation.

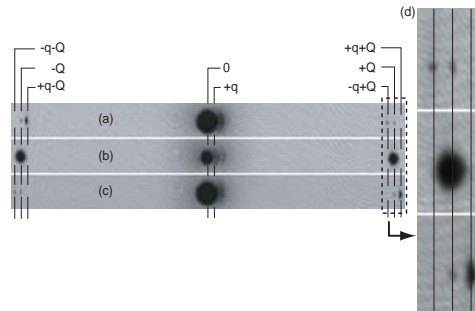


Crystallization of the vortex lattice. The top row shows three condensates that have equilibrated for 50, 150 and 300 ms, respectively, and have 48, 86 and 140 vortices recognized as “visible” by our algorithm. The bottom row shows the same condensates with the “visible” vortices circled. The field of view was 1.4 mm by 1.6 mm. The increase in visibility was shown to be independent of temperature in the range studied.

5. Experimental observation of the Bogoliubov transformation for a Bose-Einstein condensed gas

The pioneering paper by Bogoliubov in 1947 was the starting point for a microscopic theory of superfluidity [16]. Bogoliubov found the non-perturbative solution for a weakly interacting gas of bosons. The main step in the diagonalization of the Hamiltonian is the famous Bogoliubov transformation, which expresses the elementary excitations (or quasi-particles) with momentum q in terms of the free particle states with momentum $+q$ and $-q$. For small momenta, the quasiparticles are a superposition of $+q$ and $-q$ momentum states of free particles.

Following the theoretical suggestion in ref. [17] we observed such superposition states by first optically imprinting phonons with wavevector q into a Bose-Einstein condensate and probing their momentum distribution using Bragg spectroscopy with a high momentum transfer. By combining both momentum and frequency selectivity, we were able to “directly photograph” the Bogoliubov transformation [18].

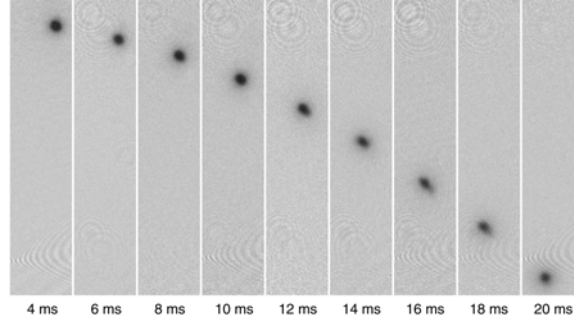


Momentum distribution of a condensate with phonons. After imprinting $+q$ phonons into the condensate, momentum analysis via Bragg spectroscopy transfers a momentum $\pm Q$ (two photon recoil) to the atoms. Absorption images after 40 ms time of flight in (a), (b), and (c) show the condensate in the center and outcoupled atoms to the right and left for probe frequencies of 94, 100, and 107 kHz, respectively. The small clouds to the right of the condensate are phonons which were converted to free particles. The size of the images is 25 x 2.2 mm. (d) The outlined region in (a) - (c) on the right is magnified, and clearly shows outcoupled atoms with momenta $Q \pm q$, implying that phonons with wavevector q/\hbar have both $+q$ and $-q$ free particle momentum components.

6. Formation of Quantum-Degenerate Sodium Molecules

A current frontier in the field of ultracold gases is the study of ultracold molecules. In 2003, several groups succeeded in converting ultracold atoms into ultracold molecules by magnetically tuning a molecular level close to zero binding energy (Feshbach resonance). Atoms can then form molecules without release of heat.

In our experiment, we produced ultracold sodium molecules from an atomic Bose-Einstein condensate by ramping an applied magnetic field across a Feshbach resonance [19]. More than 10^5 molecules were generated with a conversion efficiency of $\sim 4\%$. High phase-space density could only be achieved by rapidly removing residual atoms, before atom-molecule collisions caused trap loss and heating. This was accomplished by a new technique for preparing pure molecular clouds, where light resonant with an atomic transition selectively “blasted” unpaired atoms from the trap. Time-of-flight analysis of the pure molecular sample yielded an instantaneous phase-space density greater than 20.



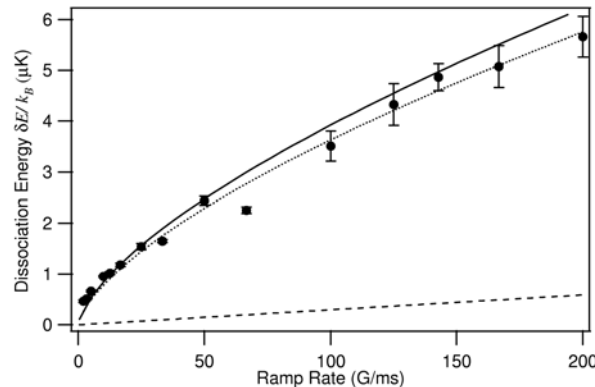
Ballistic expansion of a pure molecular sample. Absorption images of molecular clouds (after reversion to atoms) are shown for increasing expansion time after switching off the optical trap. The small expansion velocity corresponds to a temperature of about 30 nK, characteristic of high phase-space density. The images are taken along the weak axis of the trap. The field of view of each image is 3.0 mm x 0.7 mm.

7. Dissociation and Decay of Ultracold Sodium Molecules

We have studied the dissociation and decay of ultracold molecules. Sodium molecules were formed in a highly excited vibrational state by recombining two ultracold atoms [20]. An external magnetic field “tuned” the molecular binding energy close to zero (Feshbach resonance) allowing resonant recombination.

By ramping up the magnetic field, the molecular level was moved into the continuum, and the molecule dissociated. When the magnetic field ramp is very slow, the molecules follow adiabatically and end up in the lowest energy state of the atoms. The dissociation products will populate higher-lying atomic states if the ramp is fast (compared to the strength of the coupling between the molecular and atomic states). Therefore, from the observed dissociation energies, the strength of the atom-molecule coupling could be determined.

The non-linear dependence of the dissociation energy on the ramp speed reflects the Wigner threshold law for the onset of dissociation: The dissociation lifetime decreases when the molecular energy is higher above threshold. Furthermore, inelastic molecule-molecule and molecule-atom collisions were characterized. The rapid inelastic decay imposes a severe limit to further evaporative cooling.



Dissociation energy of sodium molecules as a function of magnetic field ramp rate. The dashed line represents a theoretical prediction of a linear relation, the solid line shows the result of our theory with no free parameters (using a theoretical value for the width ΔB of the Feshbach resonance), and the dotted line shows a curve with ΔB as a fitting parameter.

Listing of all publications and technical reports supported under this grant or contract

(only papers co-authored by Jamil Abo-Shaeer)

Papers published in peer-reviewed journals

1. T. Mukaiyama, J. R. Abo-Shaeer, K. Xu, J. K. Chin, and W. Ketterle:
Dissociation and Decay of Ultracold Sodium Molecules.
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Formation of Quantum-Degenerate Sodium Molecules.
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3. J.M. Vogels, K. Xu, C. Raman, J.R. Abo-Shaeer, and W. Ketterle:
Experimental observation of the Bogoliubov transformation for a Bose-Einstein condensed gas.
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Vortex Nucleation in a Stirred Bose-Einstein Condensate.
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6. A. Görlitz, J.M. Vogels, A.E. Leanhardt, C. Raman, T.L. Gustavson, J.R. Abo-Shaeer, A.P. Chikkatur, S. Gupta, S. Inouye, T. Rosenband, and W. Ketterle:
Realization of Bose-Einstein condensates in lower dimensions.
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J. Low Temp. Phys. **122**, 99-116 (2001).

Papers published in non-peer-reviewed journals or in conference proceedings

1. S. Inouye, J.R. Abo-Shaeer, P. Chikkatur, A. Görlitz, S. Gupta, T.L. Gustavson, A.E. Leanhardt, C. Raman, T. Rosenband, J.M. Vogels, K. Xu, D.E. Pritchard, and W. Ketterle:
Vortex Excitations in a Bose-Einstein Condensate.
Proceedings of the 7th International Symposium on Foundations of Quantum Mechanics in the Light of New Technology (ISQM-Tokyo '01), Hatoyama, Japan, August 27-30, 2001 (World Scientific, Singapore, 2002), pp. 122-127.

Papers presented at meetings, but not published in conference proceedings

1. K. Xu, J. Vogels, J. Abo-Shaeer, J.K. Chin, and W. Ketterle:
Generation of macroscopic pair-correlated atomic beams by four-wave mixing in Bose-Einstein condensates.
OSA Annual meeting 9/29 – 10/3/2002, Orlando, Florida, Conference Program, TuB4.
2. J.M. Vogels, K. Xu, C. Raman, J.R. Abo-Shaeer, and W. Ketterle:
Experimental observation of the Bogoliubov transformation for a Bose-Einstein condensed gas.
QELS 2002 Technical Digest, QWC2.

3. T.L. Gustavson, J.R. Abo-Shaeer, A.P. Chikkatur, A. Görlitz, S. Gupta, S. Inouye, A.E. Leanhardt, R.F. Löw, C. Raman, J.M. Vogels, D.E. Pritchard, and W. Ketterle:
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Observation of vortex lattices in Bose-condensed gas.
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9. J.M. Vogels, A. Görlitz, C. Raman, T.L. Gustavson, M. Drndic, A.E. Leanhardt, J.R. Abo-Shaeer, R. Löw, and W. Ketterle:
Realization of Bose-Einstein condensates in one and two dimensions.
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10. J. Vogels, A. Görlitz, C. Raman, T. Gustavson, M. Drndic, A. Leanhardt, J. Abo-Shaeer, R. Löw, and W. Ketterle:
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Aspects of Superfluidity in a Bose-Einstein condensate.
Bull. Am. Phys. Soc. **46**, 104 (2001).

Manuscripts submitted, but not published

None

Technical reports submitted to ARO

Regular progress reports

List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project

Jamil Abo-Shaeer, the graduate student supported by the MURI fellowship, will finish his Ph.D. thesis in the next few months.

Report of Inventions (by title only)

None

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